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14. Abstract Recently, the use of Probabilistic Risk Assessment (PRA) techniques to perform laser safety and hazard analysis for high output lasers in outdoor environments has become an increasingly accepted alternative to the traditional deterministic safety approach based on Maximum Permissible Exposure (MPE) limits. Over the past ten years, the United Kingdom (UK) Ministry of Defence (MoD) and the United States (US) Air Force Research Laboratory (AFRL) have collaborated to develop a jointly-owned, PRA-based, laser Range safety tool, the Military Advanced Technology Integrated Laser hazardD Assessment (MATILDA) system. The UK MoD has been developing PRA-based laser hazard analysis models for nearly four decades, and using them to assess laser irradiation risks to unprotected persons from laser test and training operations on UK military Ranges. The United States Air Force wishes to develop PRA-based hazard analysis models for outdoor high energy laser applications, and began the collaboration to leverage the PRA modelling expertise of the UK. Initial MATILDA code development was based on the PRA "partition" model developed to perform Range safety clearances for the UK Thermal Imaging Airborne Laser Designator (TIALD) system. MATILDA is the first military software tool to contain a complete end-to-end laser PRA model, crafted for Range applications, and with generalized terrain modelling. In the future it will provide a starting point for development of more advanced laser PRA models and tools.					
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# **MATILDA: A Military Laser-Range Safety Tool Based on Probabilistic Risk Assessment Techniques**

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**KEYWORDS:** Laser safety, Range safety, Laser hazard analysis, Probabilistic risk assessment

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## Nomenclature

$P_F$	probability of laser system fault or failure during laser firing maneuver
$\theta_{\max}$	maximum angular drift of laser sightline error
$\sigma$	root-mean-square (RMS) fault-free laser pointing error
$\alpha_{\max}$	maximum fault-free laser pointing error
$E_{\text{MOVL}}$	expected number of observers who sustain a minimum ophthalmoscopically visible lesion (MOVL) during laser firing maneuver
$E_{\text{MOVLMAX}}$	maximum acceptable value of $E_{\text{MOVL}}$
$E_{\text{CONMAX}}$	maximum acceptable value of $E_{\text{MOVL}}$ for laser firing maneuver where laser energy is inadvertently misdirected outside controlled range area (CRA)
$P_{\text{MOVLMAX}}$	maximum acceptable value of probability that irradiated individual will sustain a MOVL
$\omega$	radial line that emanates from target and crosses range boundary only once
$R(\omega)$	maximum laser firing range-to-target for aircraft approach along radial $\omega$ , assuming that fault-free laser pointing errors remain within CRA
$R_u(\omega)$	maximum laser firing range-to-target for aircraft approach along radial $\omega$ , assuming that "undershoot" fault-free laser pointing errors remain within CRA
$R_o(\omega)$	maximum laser firing range-to-target for aircraft approach along radial $\omega$ , assuming that "overshoot" fault-free laser pointing errors remain within CRA
$h$	aircraft height (or altitude)
$e_{\text{MOVL}}$	expected number of observers who sustain a MOVL for a single laser pulse, emitted during a laser firing maneuver

## 1. Introduction

Recently, the use of probabilistic risk assessment (PRA) techniques<sup>1,2</sup> to perform laser safety and hazard analysis for high output lasers in outdoor environments<sup>3-6</sup> has become an increasingly accepted alternative to standard risk analysis methods, based on maximum permissible exposure (MPE) limits.<sup>7,8</sup> Over the past 10 years, the UK Ministry of Defence (MoD) and the U.S. Air Force Research Laboratory (AFRL) have collaborated to develop a jointly owned, PRA-based, laser range safety tool, the Military Advanced Technology Integrated Laser Hazard Assessment (MATILDA) system.<sup>9-13</sup>

The move towards PRA, by some laser safety experts and organizations, has been driven by the limitations of standard, or MPE-based, risk analysis. In a standard risk analysis, exposures are simply characterized as safe or unsafe based on comparison to the MPE; no quantitative estimate of risk is provided. Standard risk analysis also implicitly assumes that risk can be completely mitigated,<sup>6</sup> giving a "sure-safe," or zero risk, condition as a final result. In controlled indoor environments, such as factories or labs, this may be true, or nearly true. In uncontrolled outdoor environments, such as military test ranges or combat operations, a true zero-risk condition is unachievable. Thus, a method giving a quantitative estimate of risk (PRA) is preferable.

PRA-based laser hazard analysis offers a number of advantages over standard risk analysis methods. First, it provides a quantified assessment of human risk (probability of injury) as a function of location. Second, it captures the probabilities and consequences of human error and laser fault/failure conditions, factors that are critical to valid hazard assessments

for military laser operations in uncontrolled outdoor environments. Third, and most importantly, PRA analysis does not assume, or require, a zero-risk condition as a final result. Instead, it compares the quantified risk against a maximum acceptable (non-zero) risk value. This produces less restrictive range clearances, while still maintaining acceptable safety levels for range personnel and members of the public. This last advantage is critical for the UK, where the small size of UK ranges and the possibility that laser beams might escape range boundaries make a zero-risk condition for range testing unacceptably restrictive.

The UK MoD has been developing PRA-based laser hazard analysis models for nearly four decades, and using them to assess laser irradiation risks to unprotected persons from laser test and training operations on UK military ranges. Over that time, PRA-based range clearance techniques have ensured the safe operation of airborne and ground-based military laser range finders and target designators during development trials and operational training exercises. Prior to the US-UK collaboration, however, the MoD had not allocated the resources to create an expert software tool like MATILDA, which performs a complete end-to-end PRA hazard analysis for airborne laser range applications, with generalized terrain modeling.

Beginning in 1998, with AFRL safety support to the Airborne Laser (ABL) and Advanced Tactical Laser (ATL) programs, the United States Air Force (USAF) had the goal of developing PRA-based hazard analysis models for outdoor high energy laser (HEL) applications. Very long HEL hazard distances, combined with the uncertainties inherent in outdoor operations, make zero risk unachievable in HEL range tests. Thus, in assessing the potential risks posed by HEL operations, a shift to probabilistic analysis is preferable. The United States began the collaboration described in this paper in order to leverage the PRA modeling expertise of the UK, with an eye to future development of an HEL PRA tool. Development of U.S. HEL PRA tools is in fact underway at this time, but it has not been completed and will not be documented here. The purpose of this paper is to document the development and capabilities of the MATILDA tool, which is currently valid only for direct beam hazards created by low-to-moderate power airborne laser designators, operating at 1064 nm, and firing at stationary targets on military ranges.

In the development of MATILDA, UK PRA modeling experience was combined with AFRL expertise in development of complex software tools for laser hazard analysis and laser range safety. Initial MATILDA code development (2007–2012) was based on the PRA “partition” model developed to perform range safety clearances for the UK Thermal Imaging Airborne Laser Designator (TIALD) system. The TIALD model “fault-free” laser hazard analysis is geometrically similar to the standard risk analysis methods currently used for laser safety clearances on U.S. ranges. However, the TIALD model contains an additional probabilistic hazard analysis component, which assesses probability of injury to an unprotected person in the event of a fault or failure in the laser directional control system. The “UK Laser PRA Model,” described in Section 2, refers to the TIALD model, as implemented in MATILDA.

The MATILDA system is a new software tool based on open-source geographic information system (GIS) technology that integrates relevant laser system performance parameters with environmental data appropriate to the range location where the system is being operated. The first 5-year project arrangement (2007–2012) to develop the MATILDA tool has been successfully completed, and a second 5-year effort (2012–2017) is currently underway to produce an updated version with enhanced capabilities. MATILDA is the first military software tool to contain a complete end-to-end laser PRA model, crafted for range

applications, and with generalized terrain modeling. In the future it will provide a starting point for development of more advanced laser PRA models and tools.

## 2. UK Laser PRA Model

### 2.1. UK need for a PRA-based approach

The primary hazard associated with low-to-moderate power lasers is potential injury to exposed tissue, and in particular the eye. While protective measures can be applied for persons within the controlled range area (CRA), the main concern—particularly in the case of airborne laser target designators and range finders—is avoidance of possible ocular injury to unprotected members of the general public, should laser energy escape the confines of the range. Traditionally, the ocular hazards associated with a laser's output have been assessed in terms of maximum permissible exposure, from which a corresponding nominal ocular hazard distance (NOHD) is determined.<sup>7,8</sup> The NOHD represents a safe viewing distance at which an observer can be exposed to the laser energy over a given period of time without risk of injury to the eye. Typical exposure periods for military laser systems can vary from the order of nanoseconds (the duration of a single Q-switched laser pulse) to as long as 10 seconds (for a stream of laser pulses).

Many military laser systems operate at wavelengths within the near infrared. Of these, 1064-nm radiation is particularly hazardous to unprotected eyesight, due to the transparency of the atmosphere and the aqueous media at that wavelength. Laser energy of sufficient intensity at 1064 nm can cause permanent scarring of the retina, with significant loss of visual acuity. The NOHD for a typical airborne laser designator emitting at 1064 nm is on the order of tens of kilometers, a hazard distance that might be substantially increased once correction factors for magnifying optics and atmospheric propagation are taken into account. We should note that the general practice in UK NOHD calculations is to include a correction factor for atmospheric scintillation, but not attenuation. In contrast, U.S. NOHD calculations generally include correction factors for atmospheric attenuation, but not scintillation.

An additional consideration in the hazard assessment is the angular spread over which laser energy may be fired. For airborne target designators and range finders especially, the wide field of regard of the laser steering mechanism, relative to the aircraft velocity vector, can produce a risk of laser energy being misdirected outside the CRA. A nominal hazard zone can be defined by sweeping the applicable NOHD over the angular range of possible directions in which the laser could be fired. It is necessary to implement adequate risk management procedures to ensure that airborne military lasers with significantly large hazard zones can be operated safely within the context of an outdoor training or test range. For a hazard assessment based on the MPE, such a requirement can be satisfied by ensuring either (a) that laser energy does not escape the CRA under any circumstances or (b) that the laser is never fired when an uncontrolled area outside the range, where unprotected persons might be present, is within the appropriate NOHD.

Where sufficient real estate is available, it is possible to ensure confinement of the hazard zone within the CRA without imposing onerous restrictions on the permitted laser firing envelope. In such cases, the laser energy is said to have been “back-stopped” within the range. U.S. ranges are typically large enough that back-stopping the beam is feasible, with the correct attack track and firing angle. Training ranges within the UK, however, are generally small in extent—of the order of a few kilometers across—and the confined ge-

ography of the UK means that training ranges are never very far from populated areas. Should hazardous levels of laser energy escape the confines of a range in the UK for any reason, it is possible that an unprotected person could be exposed to laser irradiation in excess of the MPE. In such cases the zero-risk criterion, implicit in standard risk analysis, creates a significant problem from the perspective of practical laser testing and training opportunities.

While the NOHD represents an appropriate safe exposure distance, the MPE-criterion provides no quantitative information on the probable risk of injury for unprotected observers inside the NOHD (i.e., in the hazard zone). Additionally, a strict implementation of the MPE safety standard across the entire laser field of regard does not take into account the possible variation in the risk of laser energy being fired in any given direction. With a well-designed and properly calibrated laser directional control system, it would be expected that most—if not all—of the laser energy will be reliably incident on or close to the target. In most cases then, the risk of laser energy escaping the CRA will be small.

With the relatively small size of UK ranges, the stringent limitations on the laser firing envelope, required to satisfy the MPE criterion, could totally preclude practical testing of, or training with, airborne laser systems, even though the actual risk of injury may be negligible. This implies that standard MPE-based risk analysis is generally too inflexible for UK range clearance requirements. Instead, UK range clearance models are probabilistic, and based on the principle of residual risk being “as low as reasonably practicable” (ALARP).<sup>14</sup> The use of the ALARP principle in UK hazard assessment arises from the provisions of the UK *Health and Safety at Work Act* of 1974.<sup>15</sup> Such requirements can only be satisfied by the use of a risk-based approach to laser hazard assessment. The outcome of such a risk-based assessment technique is a risk management process (see Fig. 1) by which adverse events, and the inherent uncertainties with which they occur, can be rigorously identified and mitigated.

Figure 1 provides a schematic illustration of the UK risk assessment process, which comprises two distinct stages. The *risk analysis stage* constitutes a hazard assessment of the laser system *performance* when operating either as intended, or in the event of a laser

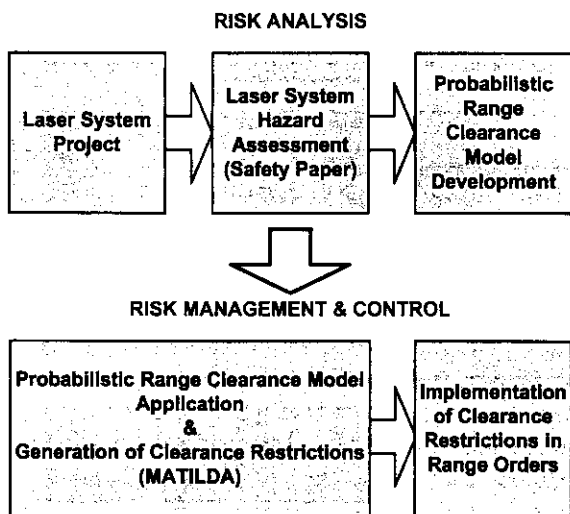


Fig. 1. Laser safety risk management process.

sightline directional control system fault or failure. The laser system hazard assessment in the UK is expressed formally in a laser safety paper (LSP), the production of which is the responsibility of the laser system project authority. The probabilistic range clearance model (PRCM) provides a means by which hazards arising from the laser system *operation* can be evaluated, and is necessarily based on the performance assessment described in the LSP. The PRCM represents the mathematical implementation of the “ $P_E$ - $P_I$ - $P_{OD}$ ” chain of adverse risk-events model. An illustration of the  $P_E$ - $P_I$ - $P_{OD}$  risk chain model, in a general risk modeling context, is provided in Fig. 2 and further discussion of the risk chain model is provided in Section 2.2.

The hazard assessment for the laser system *operation* is the subject of the *risk management and control stage*. Laser-firing restrictions for a given range, target, and attack profile combination are generated by application of the PRCM, as encoded in the MATILDA tool. The resulting restrictions on the permitted laser firing envelope may then be evaluated in context of other (non-laser) safety information, from which *actual* laser firing restrictions can be derived and promulgated to the system operators via range orders. There are hence *two* separate hazard assessments encapsulated in Fig. 1: the laser *system* hazard assessment as encapsulated in the LSP followed by the *operational* laser hazard assessment as effected by the PRCM application.

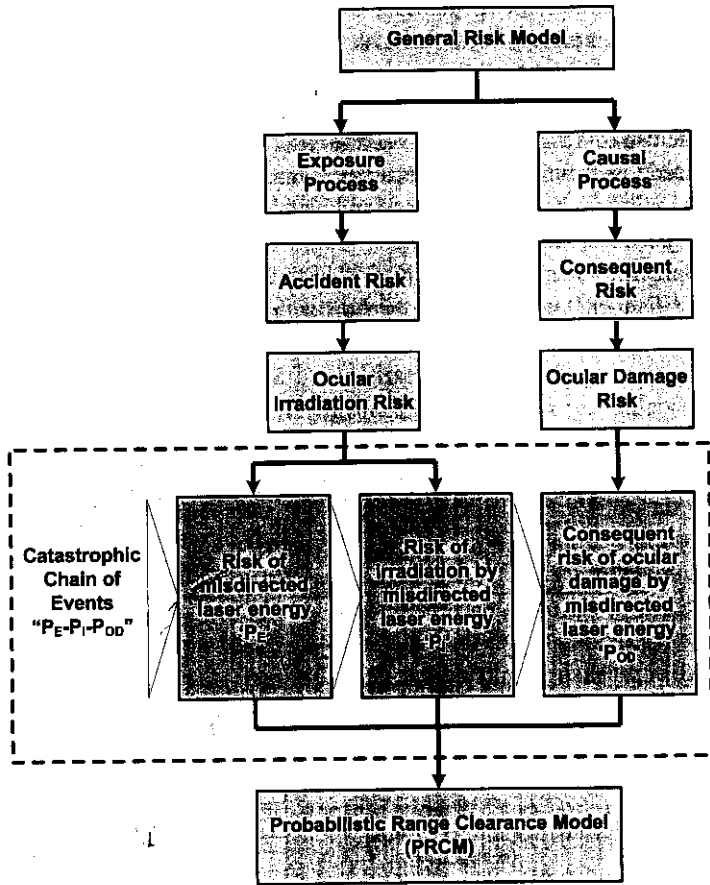


Fig. 2. “ $P_E$ - $P_I$ - $P_{OD}$ ” catastrophic chain-of-events model.

## 2.2. A risk-based approach to laser hazard assessment

The risk of an adverse event, such as a laser-induced ocular injury in an unprotected population, can be expressed in terms of a “risk chain” comprising three main components<sup>16</sup>: (1) a risk source, (2) an exposure process, and (3) a causal process (see Fig. 2). In the case of airborne laser operations, the risk source is the laser. The exposure process is the means by which laser energy from an airborne platform could be misdirected outside the CRA, causing an unprotected observer to be irradiated. The causal process is the mechanism by which that misdirected laser energy could cause an ocular injury to the unprotected observer. Uncertainty persists within both the exposure and causal processes over the occurrence of given events, such as the misdirection of laser energy in a specific direction or the sustaining of an ocular injury.

Typically, the hazard posed by a risk event can be defined by the likeliness of its occurrence and its consequent impact.<sup>16</sup> The likeliness of an adverse event can be defined in terms of the frequency or probability with which it occurs. The impact of a given event depends on the extent to which the consequences of that event affect the system under consideration. In the case of an ocular injury, the impact can vary from minimal impact on visual acuity to a total loss of visual function. The bivariate relationship between likeliness and impact can be expressed in terms of a simple “quadrant” risk model, as illustrated in Fig. 3. In this simple model, an adverse event can occur with (1) a high likeliness but low impact, (2) high likeliness and high impact, (3) low likeliness and high impact, or (4) low likeliness and low impact.

The purpose of the ALARP principle is to identify and implement suitable risk management control procedures so as to ensure that any potentially adverse events occur only with a low likeliness and low impact. An important aspect of the risk-based approach is a suitable definition of what constitutes a low likeliness and low impact event. The UK risk-based range clearance model is based primarily on a probabilistic laser pointing error model (the exposure process) coupled with a probabilistic ocular damage model for 1064-nm laser energy (the causal process).

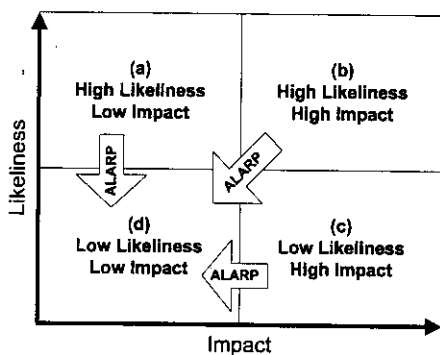


Fig. 3. Risk quadrant for an adverse event.

## 2.3. Probabilistic laser pointing error modeling

The goal of probabilistic pointing error modeling is to identify a pointing error probability distribution function (PDF), which quantifies the probability of laser energy being fired in any given direction. Clearly this function will vary, depending on the characteristics of the laser system and supporting aircraft being modeled. The UK probabilistic laser pointing error model addresses two separate regimes: (1) a “fault-free” regime, when the directional control system is operating as intended against a distinct well-defined target, and (2) a “fault/failure” regime, which covers situations when the directional control system fails to operate as intended. The latter might occur either as a result of an actual electro-mechanical

failure, or due to a failure of the system to maintain the laser sightline alignment on the target, such as during rough weather, when the aircraft is an unstable platform.

Modeling of the fault/failure condition is an important feature of the UK's risk-based range clearance technique. A significant parameter is the probability,  $P_F$ , of a laser system fault or failure occurring during the course of a laser firing maneuver, which is expected to be low for a modern, well-maintained system. A suitable value for the probability of system fault or failure can be established using appropriate fault or failure data, including mean-time-between-failure (MTBF) statistics. It should be noted that the fault/failure condition covers only accidental or unintended laser pointing errors, and not deliberate firing of the laser outside the CRA. It is assumed and required that appropriate steps are taken to disable laser firing immediately after a fault or failure has occurred, whether manually by the weapon systems operator (WSO) or automatically by built-in fault detection mechanisms. Consequently, it is expected that only a small amount of laser energy would potentially escape the confines of the CRA before laser firing ceases.

As mentioned, the definition of an appropriate PDF, which covers the fault/failure condition, is dependent on the aircraft-laser system architecture. In particular, the maximum angular drift,  $\theta_{\max}$ , of a sightline error while the laser is still active will generally be a function of system design and WSO reaction time. In the absence of suitable statistical data, an appropriate distribution function for laser directional errors in fault/failure condition can be established through the use of simulation modeling. MTBF data are used, in conjunction with a simplified "onion-skin" model (see Fig. 4), to simulate the behavior of the laser sightline following a fault or a failure in different parts of the airborne laser designator control system.

The distribution of laser pointing errors in a fault/failure condition depends on the laser system design and the consequences of any faults or failures that could occur in the directional control mechanism, all of which should be described in the LSP. Examples of directional control system failures include: a steering gimbals runaway, in which the laser sightline could be driven rapidly away from the target position, and a steering gimbals freeze, in which the laser sightline direction will depend on the aircraft motion relative to the target. Another possibility, depending again on laser system design, could involve ec-

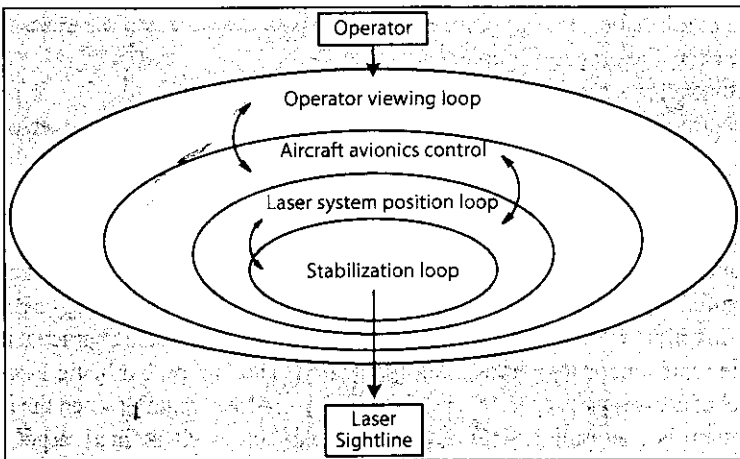


Fig. 4. SELEX ES "onion-skin" fault/failure condition model.

centric cycling of the laser sightline about the target as a result of a partial failure in the directional control system. The choice of statistical distribution representing errant laser sightline behavior is hence dependent on system design characteristics, together with the quality of information available for analysis. Statistical functions that have historically been used to describe *simple* fault pointing error models (and which are or can be encoded in MATILDA) include the uniform, triangular, and exponential distributions. More sophisticated analyses could alternatively be developed, depending on available resources and the economic justification for doing so.

Fault-free laser pointing errors are typically described using a bivariate normal distribution, defined either in local azimuth and elevation or local polar coordinates. An important parameter is the fault-free "root-mean-square" statistic,  $\sigma$ , which quantifies the statistical spread in laser pointing errors and which can be derived experimentally, using appropriate measurement data, from development trials conducted under representative conditions. Another important parameter in the UK model is a "maximum fault-free error,"  $\alpha_{\max}$ , such that the probability of an excessively large directional control error is small. Typically, the value of  $\alpha_{\max}$  will be a function of  $P_F$  and  $\sigma$  and, as such, can be considered a threshold between normally distributed fault-free laser pointing errors and fault/failure-condition laser sightline errors.

## 2.4. Probabilistic ocular damage modeling

The MATILDA tool currently uses the UK probabilistic ocular damage model, for 1064-nm laser energy, to assess the probability of injury for unprotected persons inadvertently exposed to stray laser radiation. The model is based on an experimentally derived log-normal distribution relating total intraocular (laser) energy (TIE) with the probability of causing a minimum ophthalmoscopically visible lesion (MOVL).<sup>3</sup> The UK probabilistic ocular damage model has also been combined mathematically with a probabilistic scintillation model that predicts a log-normal distribution for the multiplicative gain in laser energy density as a result of turbulence-induced, atmospheric scintillation effects.

For purposes of the UK probabilistic model, a MOVL is defined as a retinal lesion of 30- $\mu\text{m}$  diameter, assuming unaided viewing of the laser energy. The rationale behind this size of lesion is that: (1) it is practically the smallest lesion size that can be detected noninvasively using an ophthalmoscope, and (2) it is considered impractical for an infrared image smaller than 30  $\mu\text{m}$  to be formed on the retina, owing to the limitations of the human eye in imaging a distant infrared laser source. In the case of aided viewing of the laser source with magnifying optics, it is expected that the diameter of any laser image on the retina would be generally larger than the corresponding unaided image. Consequently, for aided viewing of the laser source, the MOVL diameter is increased to a value of 90  $\mu\text{m}$ .

An observer sustaining a MOVL on the most sensitive part of the retina (the fovea) could experience a minor but permanent impairment of visual acuity, such as difficulty in reading fine print. A MOVL occurring on any other part of the retina, such as the macula or paramacula, may have even less effect on visual acuity. Given other (even naturally occurring) conditions that could seriously affect visual acuity, up to and including total blindness, the effect of a MOVL can be considered to be a low-impact event.

It should be mentioned that probabilistic ocular damage models have also been developed independently by the United States (AFRL). These are "dose-response" models that give the probability of causing a MOVL (response) as a function of exposure level (dose)

for 1064 nm<sup>17</sup> and 1315 nm<sup>18</sup> laser radiation. Unlike the UK model, however, scintillation effects are not included in calculating the dose. The current plan is to include these U.S. ocular damage models in more advanced versions of MATILDA, with the user given the option of choosing the appropriate model for their particular range and training scenario.

## 2.5. UK expectation model

For airborne laser operations, the risk of ocular injury to unprotected persons can be characterized as the probability that a “catastrophic chain of events,” leading to an adverse outcome, will occur. The three main components of such a “cascade” risk are: (1) the probability of laser energy being fired in an inappropriate direction outside the CRA ( $P_E$ ), (2) the probability of an unprotected observer being irradiated by the laser energy ( $P_I$ ), and (3) the subsequent probability of the irradiated observer sustaining an ocular injury ( $P_{OD}$ ). This “ $P_E$ – $P_I$ – $P_{OD}$ ” structure provides the mathematical basis for the UK probabilistic laser hazard assessment (see Fig. 2).

The UK probabilistic hazard assessment model, or expectation model, is based on an evaluation of the expected number of unprotected observers who sustain a MOVL during an airborne laser firing maneuver, a quantity defined as  $E_{\text{MOVL}}$ . The primary criterion for clearance of a laser firing maneuver is that the expected number of cases of MOVL does not exceed a predefined maximum acceptable value,  $E_{\text{MOVLMAX}}$ . The primary criterion takes into account both the likeliness of laser energy being misdirected outside the CRA and the potential consequences of an unprotected observer being irradiated. In addition, two precautions are also implemented in the expectation model: to guard against the possibility of a low-likeliness, high-impact event, in which a high probability of ocular damage to an irradiated observer could be masked by a low frequency of occurrence.

The secondary precaution evaluates the expected hazard for a scenario in which it is assumed that laser energy is misdirected toward a populated area outside the CRA. The acceptable criterion for the secondary precaution is that—should laser energy be inadvertently misdirected outside the CRA—the expected number of cases of MOVL does not exceed a predefined maximum value,  $E_{\text{CONMAX}}$ . Finally, the tertiary precaution assumes that an unprotected observer has actually been irradiated by a single pulse of laser energy. The acceptable criterion for the tertiary precaution is that the probability of a MOVL for an irradiated individual does not exceed a predefined maximum value,  $P_{\text{MOVLMAX}}$ .

Appropriate restrictions are imposed on the laser firing envelope to ensure that the primary criterion, secondary precaution, and tertiary precaution, are all satisfied. The effect of the tertiary precaution is to impose a probabilistically defined minimum separation distance (MSD) between the laser and any unprotected observer outside the CRA. The MSD is applied in *all* directions in which the laser *could be* fired before the laser operation is inhibited, either automatically by the laser system itself or manually by the operator. In this respect, the MSD is similar to the NOHD, albeit much smaller in magnitude. An unprotected observer located at the MSD from the laser would be at a non-zero risk of sustaining a given measureable level of ocular damage, if irradiated. The role of the MSD is similar to that of a seat belt in a car. The purpose of a vehicle seat belt is to provide the occupant with a degree of protection against the possibility of a more serious injury in the event of an accident: its primary role is to mitigate the possible consequences of an accident to *an individual* rather than provide total protection against injury or death. In a similar manner, the purpose

of the MSD is to ensure against the possibility of more serious levels of ocular damage should an *individual observer* be irradiated.

## 2.6. UK partition model

The UK partition model is a specific implementation of the expectation model described above, in which the hazard contributions arising from fault-free and fault/failure operation of the laser directional control system are evaluated separately. The overall clearance restrictions defining the permitted laser firing envelope are a composite of the separately evaluated restrictions for fault-free and fault/failure operation. As mentioned previously, the partition model described here, and used in the MATILDA tool, was developed to perform range safety clearances for the UK TIALD system.

Fault-free laser firing zones (FFLFZ) are geometric areas within which an aircraft flying at a designated altitude can fire freely at the target. FFLFZ are defined in such a way that all fault-free laser pointing errors (errors less than  $\alpha_{\max}$ ) produce laser beams that fall within the CRA. Typically, the FFLFZ are evaluated for all compass directions around the target, and over a range of aircraft altitudes, in accordance with laser system user requirements. Each designated aircraft altitude produces a different FFLFZ. The geometry of the FFLFZ calculation is similar to the standard risk analysis methods currently used by the USAF to establish a safe laser firing envelope.<sup>10</sup> However, the FFLFZ calculation is designed to maximize the range-to-target at which the laser can be fired, given the extent of CRA available.

The hazard analysis for fault/failure operation is the fully probabilistic portion of the overall laser hazard assessment. It follows computation of the FFLFZ, considers laser pointing errors in excess of  $\alpha_{\max}$ , and is only performed for specific laser firing maneuvers on specific aircraft attack tracks. Thus, the first step in the fault hazard analysis is to define the aircraft attack track, attack altitude, and laser firing positions. A check is then made to ensure that the attack scenario complies with FFLFZ restrictions. Any laser firing maneuvers that do not comply with FFLFZ restrictions are eliminated prior to the fault hazard analysis.

The probabilistic laser pointing error model and probabilistic ocular damage model are used in the fault hazard analysis to evaluate  $E_{\text{MOVL}}$ , and this is compared to the maximum acceptable value,  $E_{\text{MOVLMAX}}$ , to determine whether the specified laser firing maneuver meets the primary criterion for safety clearance. A typical maximum acceptable expectation value for UK range clearances is  $10^{-8}$  occurrences of MOVL per attack. In comparison, a typical NASA acceptable expectation value for injury by falling inert debris is  $10^{-6}$  injuries per launch. If the primary criterion is met, then the secondary and tertiary precautions are applied, to identify any additional restrictions on the laser firing envelope.

The partition model is a means by which the conditional expectation of a MOVL in an unprotected population can be evaluated, and appropriate laser firing restrictions defined, such that risks produced by a specified laser firing maneuver are kept within acceptable limits. In terms of the quadrant risk model (Fig. 3), the FFLFZ ensures that all high likeliness events, whether of high or low impact, are contained within the controlled range area. Furthermore, the subsequent fault hazard analysis ensures that appropriate additional restrictions are defined to avoid the occurrence of low likeliness, but potentially high impact events. In this respect, the partition/expectation model satisfies the ALARP requirement.

## 2.7. Computational model

The partition/expectation model is implemented by means of the computational model, from which the applicable laser firing restrictions are derived. The computational model is composed of three main modules, executed sequentially, called RBPROG, CALCZONE, and CALCFAULT. In these modules input data required for the hazard assessment—such as range boundaries, terrain elevation data, target position on the range, local demographics, local geography near the range, and aircraft and laser system parameters—are first specified. Appropriate preliminary computations, including definition of the CRA, are then performed, followed by the execution of the partition model as described above.

The initial module is the range boundary program, known as RBPROG for short. The main purpose of the RBPROG algorithm is to define the CRA, which will be used in the CALCZONE module to define the FFLFZ. The CRA is a subset of the total range area, which is “star-shaped” with respect to a given target. A CRA is defined to be star-shaped when any radial,  $\omega$ , emanating from the target, crosses the range boundary only once. Frequently the initial range area does not satisfy the star-shaped condition, so a portion of it is truncated to form the star-shaped CRA. Extra coordinates are also inserted around the modified CRA boundary to provide appropriate computation points for the CALCZONE algorithm.

The second module, CALCZONE, performs the fault-free laser hazard analysis. Specifically, it calculates the FFLFZ for each designated target within the CRA, and for each designated aircraft altitude. The definition of an FFLFZ begins with a set of radials connecting the target to each of the CRA boundary points. For each radial,  $\omega$ , emanating from the target, CALCZONE computes a maximum laser firing range-to-target (ground range),  $R(\omega)$ , such that fault-free laser pointing errors (within  $\alpha_{\max}$  of the laser–target vector) remain within the CRA. This requirement results in two such ranges-to-target,  $R_u(\omega)$  and  $R_o(\omega)$ , corresponding to the need to keep “undershoot” and “overshoot” laser pointing errors, respectively, within the CRA, as shown in Fig. 5. We should note that azimuth errors are generally not significant compared to elevation (i.e., undershoot or overshoot) errors. We should also note that Fig. 5 shows the aircraft firing when not directly over the range, something not usually done during U.S. laser range tests. This is allowed under UK laser safety policy, due to their small ranges, but only on fixed approaches and at fixed heights, as indicated by the fault-free laser firing cones (FFLFZ).

The applicable maximum range-to-target,  $R(\omega)$ , at which the laser may be fired is taken to be the smaller of the undershoot and overshoot ranges; that is,  $R(\omega) = \min\{R_u(\omega), R_o(\omega)\}$ . Since the firing angle to the target will vary with aircraft height (or altitude),  $h$ , a different set of maximum firing ranges will be obtained for each designated aircraft altitude. The FFLFZ for each aircraft altitude can then be defined as the set  $\{R(\omega): \omega \in [0, 2\pi)\}$ . For any aircraft maneuver, at any given altitude, the FFLFZ defines the maximum range-to-target at which the laser may be fired, assuming fault-free operation of the laser directional control system.

The third module, CALCFAULT, performs the probabilistic fault/failure hazard analysis for a specific laser attack scenario to determine if any additional restrictions must be imposed on the laser firing envelope permitted by the FFLFZ. As mentioned previously, the first step in the fault hazard analysis is to define the aircraft attack track, altitude, and laser firing positions. A check is then made to ensure that the laser attack scenario complies with FFLFZ restrictions and any laser firing maneuvers that do not comply are eliminated.

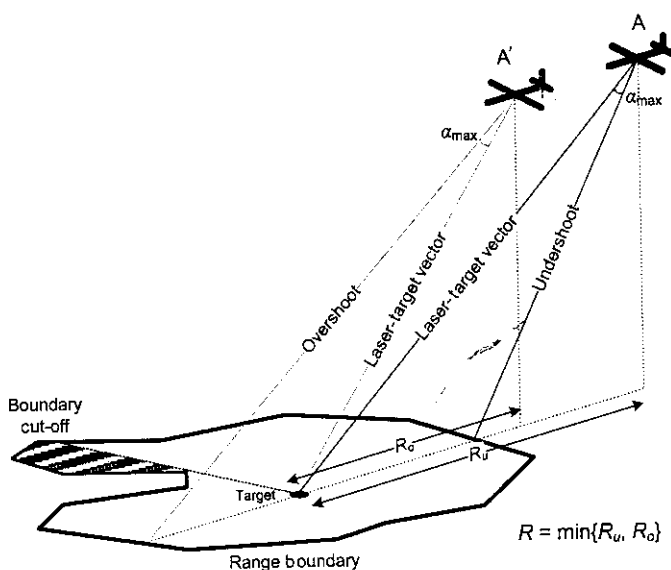


Fig. 5. Fault-free overshoot and undershoot.

For each laser pulse fired during the course of the specified laser attack scenario, the CALCFAULT algorithm evaluates a corresponding expectation value,  $e_{\text{MOVL}}$ , that a MOVL will occur in the unprotected population surrounding the CRA. The number of pulses emitted after a fault or failure has occurred depends on the pulse repetition frequency and the length of time required for the laser to cease firing. Consequently, the overall expectation value,  $E_{\text{MOVL}}$ , of MOVL occurring in the unprotected population, is the sum of the individual (pulse-based)  $e_{\text{MOVL}}$  values for the period of time during which the laser continues to fire, and before laser firing is inhibited.

Restrictions on laser firing are subsequently imposed on those portions of the aircraft maneuver for which the calculated value of  $E_{\text{MOVL}}$  exceeds the acceptable limit. Additional laser firing restrictions may also be imposed on those portions of the aircraft maneuver that bring the laser to within the applicable MSD of potentially vulnerable populated areas. The computational model requires a significant amount of geographic and demographic data in order to compute an optimum set of restrictions for any given laser firing operation during a training maneuver. The MATILDA tool is designed to provide a suitable software platform for performing these calculations and displaying the results, based on geographic information system technology tailored to the needs of airborne military laser hazard assessment.

### 3. The MATILDA Tool

#### 3.1. Genesis of MATILDA

During the early 1990s, the USAF identified the need for an automated software tool to aid range safety officers in establishing laser range safety clearances. The result was the Laser Range Management Software (LRMS) tool, which the USAF's Optical Radiation Safety team has used for nearly two decades to establish MPE-based range safety clearances for all USAF active ranges. During the late 1990s, the USAF began attempts to understand the

safety implications of developing high energy laser systems. Initial developments followed the accepted standard risk analysis approach, but it was recognized by AFRL that eventually a PRA-based tool would be necessary to deal with HEL hazard analysis in support of range testing, training, and operational deployment. It was at this time that discussions with the UK MoD began, with the goal of leveraging their laser PRA modeling capabilities.

Early discussions focused on each organization's respective methodologies for laser safety and hazard analysis. After consideration, it was agreed that the best way to clarify U.S. understanding of the UK PRA-based approach was to actually implement one of the existing UK models, using AFRL expertise in development of advanced software tools for laser hazard analysis. By approaching the collaboration in this manner, the USAF has realized its goal of understanding UK methodology, and the UK has realized its goal of obtaining an integrated version of their laser PRA analysis methodology in a single analytical tool. It was decided that the best candidate for this effort would be the PRA partition model for the UK Thermal Imaging Airborne Laser Designator (TIALD) system. The UK also suggested that the new software be called the Military Advanced Technology Integrated Laser Hazard Assessment (MATILDA) tool.

### 3.2. MATILDA development and testing

The UK MoD's TIALD model consisted of several HP BASIC programs that had been developed and refined over many years. Each program was a stand-alone code whose results were manually fed to the next program in the analysis chain. Geographic input data were manually extracted from British Ordnance Survey maps. Although an independent implementation of TIALD model algorithms has been created in MATILDA, the results of these original codes have proven valuable as a cross-check on MATILDA results.

During MATILDA development, the UK MoD has supplied the mathematical models, algorithms, and corresponding documentation, while the USAF has been the primary software developer. A lesson learned from earlier generations of laser codes was to encapsulate computational logic/code into a nonproprietary language to avoid continuous porting of the code to the latest fad in software tools. FORTRAN has long been that language but has been losing ground to C and C++ over the last couple of decades. Thus, MATILDALib is an ANSI C++ library that encapsulates all of the computational code and logic required of RBPROG, CALCZONE, and CALCFAULT. Using C/C++ provides MATILDALib the speed advantages inherent in C/C++ codes while also providing portability to most modern computing platforms.

Although MATILDA started out as a computational tool, and retains a computational focus, the need to display the results graphically became readily apparent during the initial implementation of the RBPROG algorithms. The original HP BASIC codes implemented a scaled version of the British National Grid Coordinate system. Early discussions between the UK MoD and USAF had already emphasized the need to leverage standard geographic information system (GIS) formats; however, budgets on both sides were limited. Fortunately for us, the Idaho State University (ISU) Geospatial Software Lab (GSL) had similar constraints several years earlier, when they launched the MapWindow Open Source development effort. After a quick study of the ISU GSL capabilities, it was decided that MATILDA should consist of a set of plug-ins to MapWindow.

The MATILDA development team has made a concerted effort to keep the computational engine of the tool, MATILDALib ANSI C++, completely independent of the Map-

Window code. Separating the graphics user interface (GUI) from the computational engine has a number of advantages. It simplifies coding, debugging, and updates of the different modules of the tool, enhances portability to different platforms, and allows MATILDALib to be leveraged by any GIS application/system. This is important because, just as the MATILDA project has leveraged MapWindow efforts, future PRA applications will be able to leverage the MATILDA effort.

Due to the diverse requirements for generating range clearance information, it was agreed that there should actually be three different versions of MATILDA. The first (MATILDA User) would be for basic users to simply determine whether a particular mission was allowed, based on an established range clearance, and with little or no ability to change any of the previously verified and tested input parameters. The second (MATILDA User Plus) would be for more advanced users at the range to incorporate limited changes to the target position and attack track. The third (MATILDA Pro) would be the full model for expert analysts responsible for setting the parameters needed for the range safety analysis and then performing the analysis to establish the initial range clearance.

### 3.3. Sample MATILDA analysis

As a demonstration of code capabilities, we used the MATILDA Pro version to perform a sample hazard analysis for a hypothetical airborne laser designator used in an attack maneuver during a range training scenario. It is assumed that the laser designator is an "all-round line-of-sight" system mounted on a single-seat strike aircraft. First an analysis of the laser output during the attack maneuver must be carried out. Typically, the laser will be fired in short bursts of a few seconds duration at different points on the attack track.

Important parameters for the laser hazard analysis include: (1) details of the pulse energy, peak irradiance, and beam energy distribution, which may change considerably during the course of the attack maneuver as the laser warms up or cools down; (2) other key beam parameters such as wavelength, beam divergence, pulse duration, and pulse repetition frequency; (3) fault-free and fault pointing error distributions; and (4) the probability of fault for the laser system. These laser system parameters are obtained by the laser system manufacturer through testing of multiple laser units and averaging of performance data. The data are provided to laser safety officers in the laser safety paper (LSP) described in Section 2.1. The LSP is compiled by the laser system project authority and represents the laser system hazard assessment. Hypothetical laser system parameters for input into MATILDA are summarized in Table 1.

**TABLE 1.** Input Parameters for Hypothetical Airborne Laser Designator

Parameter	Parameter Value
Fault-free pointing error distribution	Gaussian
Fault-free RMS pointing error	5 mrad
Fault pointing error distribution	Uniform
Maximum fault pointing error	0.35 rad (20 deg)
Probability of fault	$10^{-4}$ per attack
Laser switch-off time in fault condition	3 seconds
Laser wavelength	1064 nm
Pulse energy	200 mJ
Beam divergence	0.124 mrad
Pulse duration	10 ns
Pulse repetition frequency	20 Hz

In addition to laser system parameters, MATILDA also requires a great deal of geometric and geographic input data such as range boundaries, terrain mapping data, terrain elevation data, target position on the range, location of urban areas, and local geography near the range. Geometric inputs of this kind are represented visually by shapes on layers loaded by the analyst, as shown in Fig. 6. Once all necessary input data have been entered, the three main modules—RBPROG, CALCZONE, and CALCFAULT—are executed sequentially.

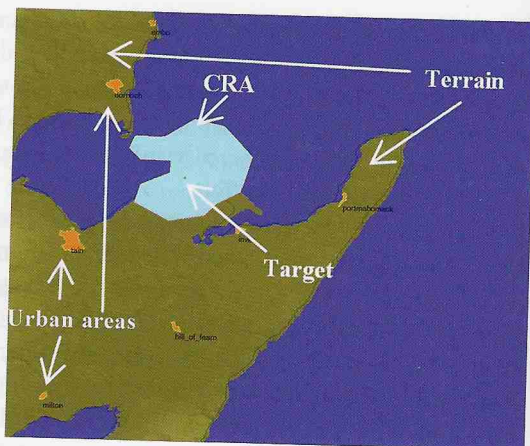


Fig. 6. MATILDA Pro primary geographic inputs.

### 3.4. RBPROG analysis

The main purpose of the RBPROG module is to define a CRA suitable for use in the CALCZONE module. A suitable CRA is defined to be a subset of the total range area that is “star-shaped” with respect to a given target; that is, any radial emanating from the target crosses the CRA boundary only once. The RBPROG analysis achieves this result via six steps: (1) the “star-shaped” condition, (2) the “points of approach” condition, (3) the “terrain profile” condition, (4) the “urban area” condition, (5) the “small increment” condition, and (6) the “undershoot/overshoot” condition.

The star-shaped condition establishes the suitability of the CRA boundary for the application of the CALCZONE module. Essentially, the star-shaped condition ensures that a radial from the target position crosses the CRA boundary once only. The points of approach condition is designed to identify the closest point to the target on a line segment making up part of the CRA boundary, so that the fault-free laser firing zones can be properly evaluated. Line segments are subdivided to ensure the validity of this condition. In MATILDA, the surrounding (non-flat) terrain can be represented in terms of a stepped terrain profile model, which is defined radially with respect to the target position. The terrain profile model provides a means of ensuring against the possibility of short-range irradiation of elevated terrain areas under the laser–target vector, where unprotected persons might be present. A terrain profile is a simplified representation of an actual landscape, based on an ascending terrain step function. Terrain steps are defined within an angular sector at given radial distances from the target. Fig. 7 illustrates a terrain profile example in which the terrain steps are defined at 1-km intervals, within 10-degree sectors centered on the target. The CRA boundary is indicated by a dashed line. The height of each step in an angular sector is defined by the highest of the maximum spot heights within the step, or the height of the previous step nearer the target.

The extent of the fault-free laser firing zones (FFLFZ) can be affected by the underlying terrain step profile. Thus, it is important that the FFLFZ are evaluated using the correct underlying terrain step profile. The purpose of the terrain profile condition is to insert additional coordinates at the points of intersection between the line segments making up

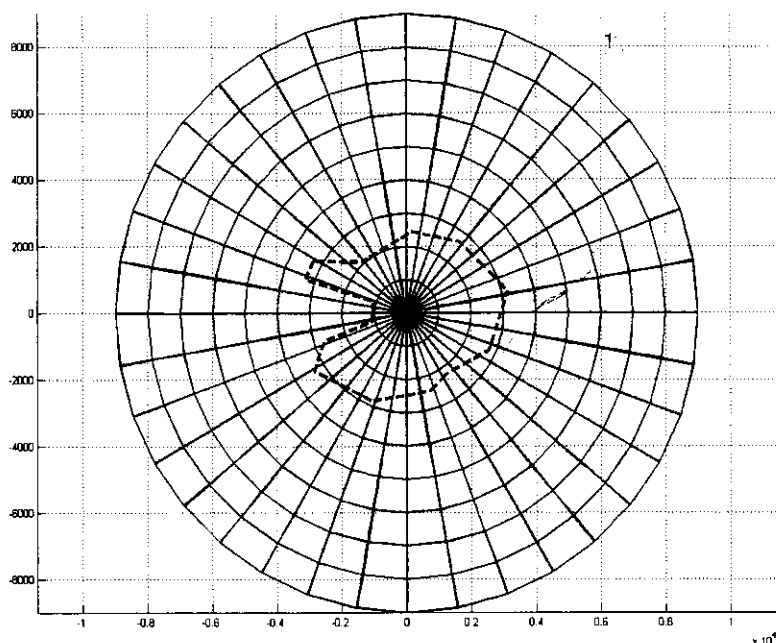


Fig. 7. Terrain profile "web."

the CRA boundary and the terrain profile sector radials, so that the different analytical layers making up the overall clearance solution can be properly aligned geographically.

The urban area condition adds boundary points to the CRA that correspond with radials that subtend each urban area in the vicinity of the range. The small increment condition ensures that a maximum of 0.5 degrees is maintained between the CRA boundary points. Additional boundary points may be added as required. The undershoot/overshoot condition ensures that each CRA boundary point is mirrored by a diametrically opposite boundary point relative to the target. A new boundary point is added to the CRA if such a "mirror point" does not exist. Collectively these six steps result in a set of boundary coordinates along the CRA boundary that will be used subsequently by CALCZONE. The CRA boundary points are used to calculate the permissible laser firing distances at various compass points around the target, that is, the fault-free laser firing zones. A sample CRA generated by the RBPROG module is shown in Fig. 8. The CRA boundary is in red and black, with the black line representing an alteration to the range boundary needed to satisfy the star-shaped condition.

### 3.5. CALCZONE analysis and attack track definition

The second module, CALCZONE, performs the fault-free laser hazard analysis; that is, it calculates the fault-free laser firing zones (FFLFZ) for each designated aircraft altitude, and the specified target position, using the CRA defined in RBPROG. The procedure for this has been previously described in Section 2.7. For any aircraft attack track, at any given altitude, the corresponding FFLFZ defines the maximum range-to-target at which the laser

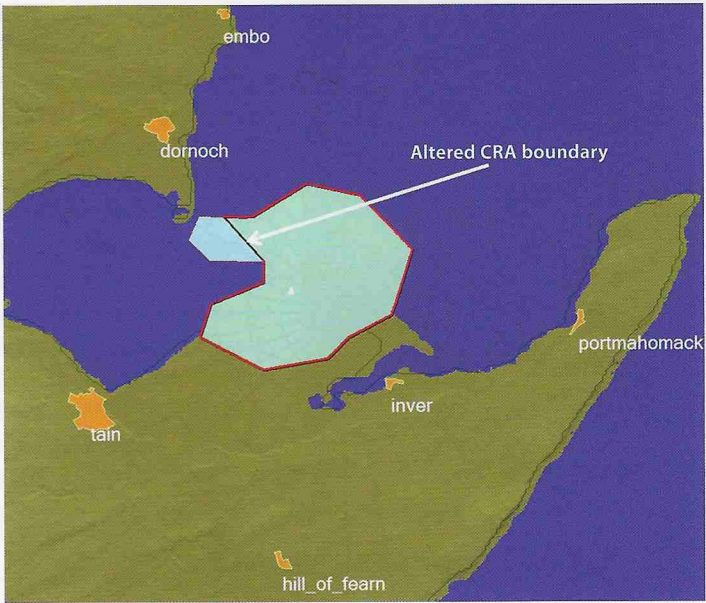


Fig. 8. RBPROG analysis result: CRA with additional boundary points.

may be fired, assuming fault-free operation of the laser directional control system. The FFLFZ provide the analyst and range personnel with a fault-free operating envelope. An example of the FFLFZ contours, specifying firing zones for different altitudes, generated and displayed by MATILDA, is shown in Fig. 9.

Generation of the FFLFZ completes the fault-free laser hazard analysis and lays the foundation for the probabilistic fault/failure hazard analysis performed in CALCFAULT. Prior to execution of CALCFAULT, however, a specific laser attack scenario must be defined. MATILDA provides a feature, the Attack Track Waypoint Editor, that allows an analyst to overlay an attack track, defined by a series of waypoints, onto the map. The data entry for waypoints includes waypoint coordinates, aircraft altitude, aircraft velocity, and whether the laser is firing at that waypoint. With these data, MATILDA compares the proposed attack track against the altitude limitations defined by the FFLFZ and indicates to the analyst those portions of the track that are cleared for laser firing and those where laser firing is prohibited. Fig. 10 gives an example of such a user-entered attack track. Note that the vast majority of the attack track is colored green, and hence cleared for firing, but a small portion at the end violates FFLFZ altitude limitations, and is therefore colored red. Only the portion of the attack track that clears FFLFZ restrictions is analyzed during CALCFAULT execution.

### 3.6. CALCFAULT analysis

The third module, CALCFAULT, performs the probabilistic fault/failure hazard analysis for the designated and cleared laser attack scenario, to determine if any additional restrictions must be imposed on the laser firing envelope permitted by the FFLFZ. The CALCFAULT analysis quantifies the actual risk for firing along the designated attack track, in the event of

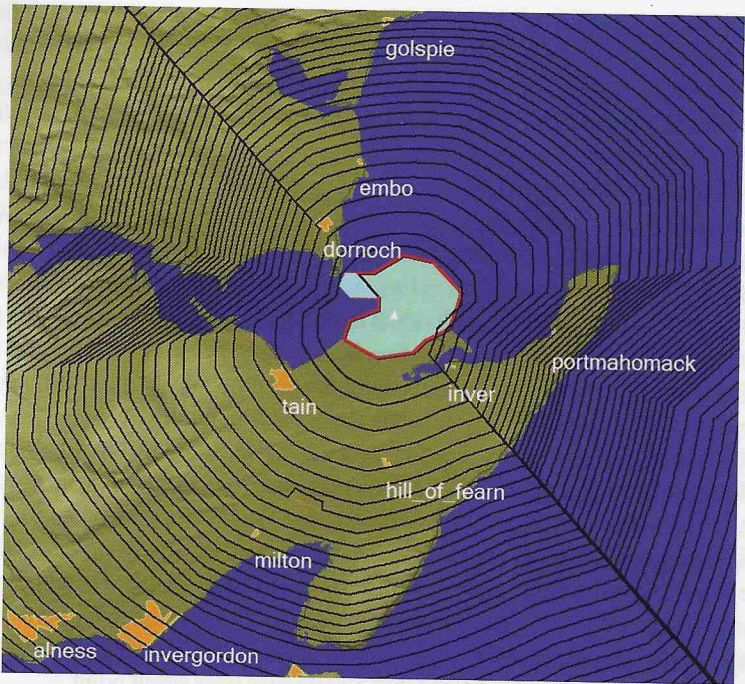


Fig. 9. MATILDA-generated fault-free laser firing zones.

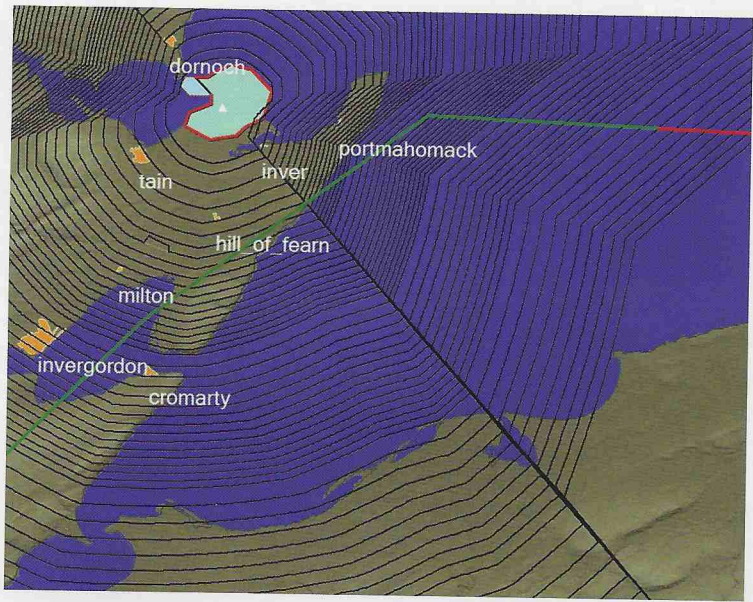


Fig. 10. Fault-free, attack track check.

a fault in, or a failure of, the laser directional control system. The probabilistic laser pointing error model and probabilistic ocular damage model discussed in Section 2 are used in this analysis. Key input parameters for the CALCFAULT analysis include laser system parameters,

attack track data, population densities of the urban areas surrounding the range, the terrain computational grid (points on the ground for which ocular damage probability is computed), and of course, the maximum acceptable value of the overall damage probability,  $E_{\text{MOVLMAX}}$ .

For each laser pulse fired during the course of a specified aircraft attack track, the CALCFAULT algorithm evaluates a corresponding expectation value,  $e_{\text{MOVL}}$ , that a MOVL will occur in the unprotected population surrounding the CRA. The number of pulses emitted after a fault or failure has occurred depends on the pulse repetition frequency (PRF) and the length of time required for the laser to cease firing (maximum duration of fault firing). Consequently, the overall expectation value,  $E_{\text{MOVL}}$ , of a MOVL occurring in the unprotected population, is the sum of the individual (pulse-based)  $e_{\text{MOVL}}$  values for the period of time during which the laser continues to fire, before laser firing is inhibited. Restrictions on laser firing are subsequently imposed on those portions of the aircraft maneuver for which the calculated value of  $E_{\text{MOVL}}$  exceeds the acceptable limit.

For the current analysis, MATILDA first uses the 20-Hz PRF and the user-defined attack track to determine the location of each pulse emitted during an attack. These laser firing points are then used to determine a beam footprint whose boundaries are defined by the maximum pointing error entered (20 degrees). The only terrain grid points evaluated for each  $e_{\text{MOVL}}$  are those that fall within the area defined by the beam footprint. The number of these areas actually considered for  $E_{\text{MOVL}}$  is dependent on the PRF and the maximum duration of fault firing, which indicate how many total pulses need to be evaluated, assuming that a laser control error occurs when the aircraft reaches a particular laser firing point.

Since there is uncertainty in knowing when the fault will occur, the  $E_{\text{MOVL}}$  calculation must be carried out for a possible laser control error occurring at each laser firing point in the entire engagement. The goal is to limit the value of  $E_{\text{MOVL}}$  for any possible failure scenario to the maximum acceptable value,  $E_{\text{MOVLMAX}}$ . In the case of the analysis shown here,  $E_{\text{MOVLMAX}}$  was  $10^{-8}$ . If any  $E_{\text{MOVL}}$  value for any possible failure scenario is found to exceed  $E_{\text{MOVLMAX}}$ , then the analyst has a choice of either converting that section of the attack track to a prohibited firing region, or modifying the attack track to reduce the  $E_{\text{MOVL}}$  value.

Figure 11 shows a comparison of all  $E_{\text{MOVL}}$  values to the acceptable risk threshold. The 5200  $E_{\text{MOVL}}$  values plotted in Fig. 11 are calculated for a possible laser control error occurring at each of 5200 possible laser firing positions, along the FFLFZ-cleared attack track shown in Fig. 10. Each  $E_{\text{MOVL}}$  value consists of the sum of 60  $e_{\text{MOVL}}$  values, representing the 60 pulses fired during the 3-second shutdown period following the control error. In this case, the FFLFZ-cleared attack track does not exceed the ac-

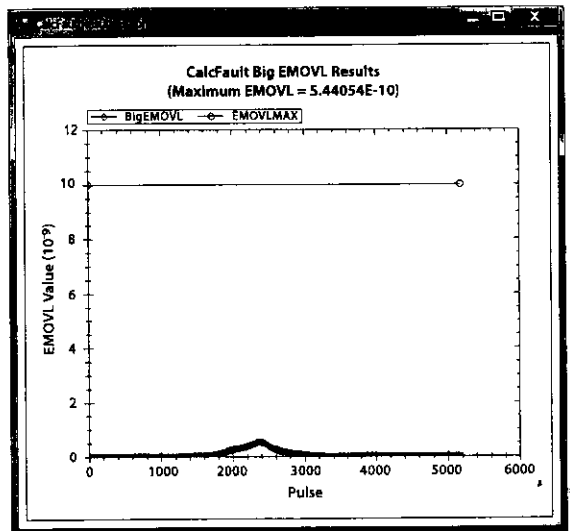


Fig. 11. Comparison of  $E_{\text{MOVL}}$  values to  $E_{\text{MOVLMAX}}$  criterion.

ceptable risk threshold for a laser control error at any of the 5200 firing points. It would therefore be approved for laser firing without modification.

#### 4. Discussion

The concept of PRA and its application to military laser safety in outdoor environments has been gaining in ascendancy in recent years, as the advantage of, and the necessity for, a probabilistic approach to laser hazard analysis has become increasingly accepted. The advantage of a PRA-based solution over the standard risk analysis method involving evaluation of the NOHD is amply illustrated in Fig. 12, in which a deterministic ocular hazard zone (DOHZ), based on the single-pulse NOHD, is compared with a probabilistically derived laser hazard area trace (LHAT) that has been defined for all laser pulses emitted during the attack sequence. In this case, the PRA-based LHAT is much smaller in extent than the DOHZ. Additionally, the variation of risk with location inside the LHAT can be evaluated, whereas the interior of the DOHZ can only be described as “unsafe.” As an example of how this might benefit the DOD, AFRL personnel have done probability of injury analysis, as a function of location of ground observers, for reflections from airborne ordnance targeted by Army ground-based laser systems.

PRA-based methods are thus perceived to offer greater flexibility to the laser system operator, while maintaining acceptable levels of safety for unprotected members of the gen-

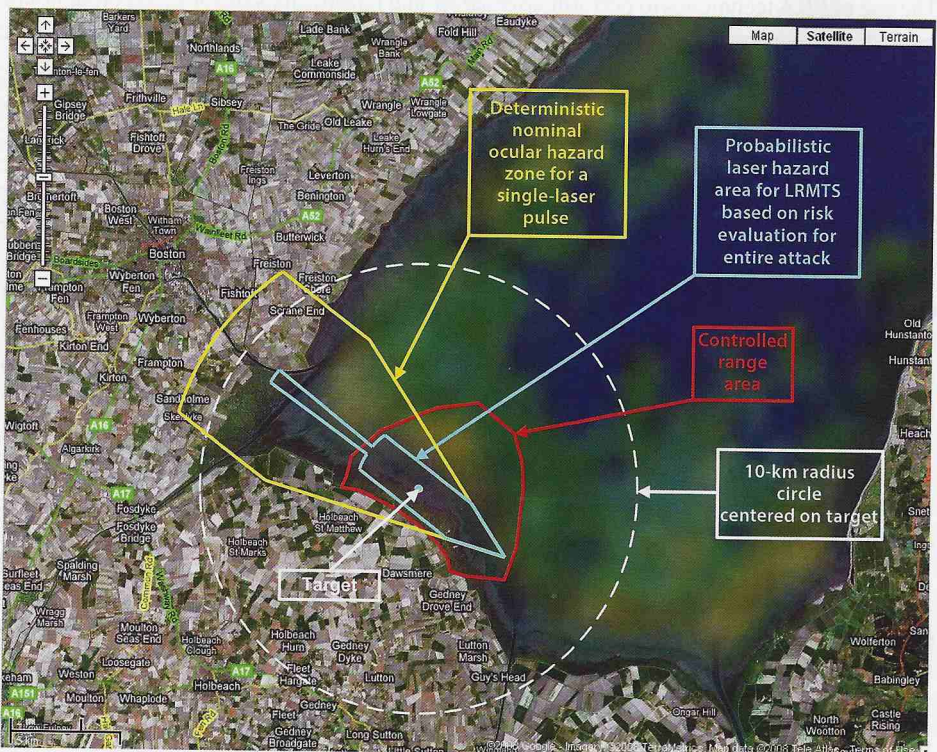


Fig. 12. Comparison of PRA-based laser hazard area trace with deterministic ocular hazard zone.

eral public. On the other hand, the PRA-based method does not come without additional cost. Due to the smaller margins of safety involved in the PRA method, based on what is deemed to satisfy the ALARP principle, a substantial amount of preliminary effort is required to establish the performance attributes of the laser system and ensure the validity of the subsequent hazard analysis. The Laser System Safety Investigation (LSSI) needed to adequately characterize the fault-free performance and fault/failure characteristics of the laser directional control system, has been described in detail in a previous publication.<sup>13</sup>

Perhaps the most important requirement of the PRA-based clearance method is the determination of what level of risk is deemed to be acceptable to unprotected members of the general public in the vicinity of laser system test or training operations. The acceptable level of risk will vary from one jurisdiction to another, and should be decided at an appropriate policy level within the host country's chain of executive responsibility. As mentioned in Section 2.6, the maximum acceptable risk level set by the UK MoD is  $10^{-8}$  occurrences of MOVL per attack. There is currently no acceptable risk level specified for U.S. ranges, because PRA is still too new in Department of Defense applications. The identified acceptable level of risk will have an impact on the flexibility of the resulting clearance restrictions. In general, the more stringent are the safety criteria, the less flexible will be the resulting clearance restrictions.

## 5. Conclusion

The use of PRA techniques to perform laser safety and hazard analysis for high output lasers in outdoor environments has become an increasingly accepted alternative to standard risk analysis methods, based on MPE limits. Over the past 10 years, the UK MoD and the U.S. AFRL have collaborated to develop a jointly owned, PRA-based, laser-range safety tool, the MATILDA system.

PRA-based laser hazard analysis offers a number of advantages over standard risk analysis methods. First, it provides a quantified assessment of human risk (probability of injury) as a function of location. Second, it captures the probabilities and consequences of human error and laser fault/failure conditions, factors which are critical to valid hazard assessments for military laser operations in uncontrolled outdoor environments. Third, and most importantly, PRA analysis does not assume, or require, a zero risk condition as a final result. Instead, it compares the quantified risk against a maximum acceptable (non-zero) risk value. This produces less restrictive range clearances, while still maintaining safety levels deemed acceptable for range personnel and members of the public. This last advantage is critical for the UK, where the small size of UK ranges and the possibility that laser beams might escape range boundaries make a zero risk condition for range testing unacceptably restrictive.

Over the past four decades, the UK MoD has pioneered the development of PRA-based models for laser hazard assessment, using them to assess laser irradiation risks to unprotected persons from outdoor test and training operations on UK military ranges. The USAF has also identified the need for a PRA-based approach in the quantification of laser hazards. Discussions between the USAF and the UK MoD revealed a common objective in developing a jointly owned, PRA-based, laser range safety tool. Thus, UK laser PRA modeling expertise and AFRL expertise in development of advanced laser hazard assessment tools were combined to create the MATILDA tool.

The MATILDA system is a new software tool based on open-source GIS technology that integrates relevant laser-system performance parameters with environmental data appropriate to the range location where the system is being operated. It provides a modern, low-cost, portable computational environment, which may be tailored equally to the needs of the local range safety technician and the expert analyst. MATILDA provides the user/analyst with the means to efficiently assess risks arising from different attack profiles on any given target, and ensures that the results are consistent with acceptable safety criteria. The result is an optimum level of flexibility in laser range operations, while still maintaining high standards of safety for unprotected persons near the range. MATILDA is the first military software tool to contain a complete end-to-end laser PRA model, crafted for range applications, and with generalized terrain modeling. In the future it will provide a starting point for development of more advanced laser PRA models and tools.

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